N73-

Paper W 1

HYDROGEOLOGY OF CLOSED BASINS AND DESERTS OF SOUTH AMERICA, ERTS-1 INTERPRETATIONS[1]

George E. Stoertz and William D. Carter, *U. S. Geological Survey, Washington, D. C. 20244*

ABSTRACT

Images from the Earth Resources Technology Satellite (ERTS-1) contain data useful in studies of hydrogeology, geomorphology, and paleoclimatology. Sixteen Return Beam Vidicon (RBV) images and 15 Multi-Spectral Scanner (MSS) images were studied. These covered deserts and semidesert areas in southwestern Bolivia, northwestern Argentina, northern Chile, and southeastern Peru from July 30 to November 17, 1972. During the first 3 months after launching, high-quality cloud-free imagery was obtained over approximately 90 percent of the region of interior drainage, or an area of 170,000 square miles.

Hydrologic applications of ERTS imagery made evident by studies to date include: 1) mapping of salars or salt-encrusted playas, which represent water discharges from closed drainage basins; 2) mapping of drainage divides, particularly around closed basins in dry regions; 3) mapping of geologic structural data, related to origin and hydrologic closure of basins; 4) revision of geologic maps to show hydrologically important differences in surficial deposits; 5) revision of hydrologic features on topographic maps; 6) monitoring seasonal changes in floodwaters to evaluate areal and seasonal changes in weather, climate, and water resources; 7) mapping of mountain snowpack; and 8) relation of permanent drainage basin characteristics to seasonal snow cover and floodwater as an aid in estimating water resources of basins lacking meteorological or stream-gaging stations.

1. SCOPE OF THE STUDY

Cloud-free ERTS-1 coverage of the study area was approximately 90 percent complete between July 30 and October 30, 1972, comprising 16 RBV and 15 MSS images. This 3-month period represents mid-

1/ Publication authorized by the Director, U.S. Geological Survey.

winter and early spring, the period of extensive snow cover in midwinter, of heavy snowpacks in the high Andes in early spring, of extensive surface water on floodplains in closed drainage basins, of moderately high ground water levels beneath salars, and of increasing spring discharge along the periphery of salars.

The study area (Figure 1) covers most of Areas 7 and 9 in a

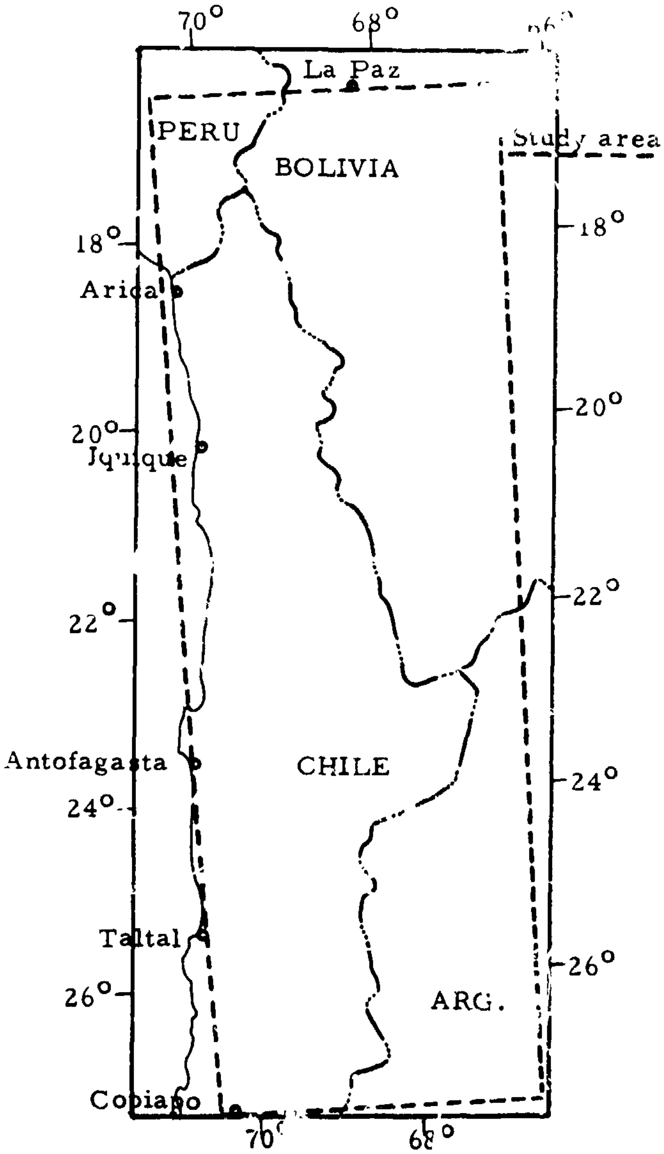

FIGURE 1. ERTS STUDY AREA

NASA-approved ERTS-1 investigation (ID IN-012); it coincides with the area of a proposed ERTS-B investigation (Proposal 22010).

Cloud-free ERTS coverage during this season prevailed except in the southwest, from latitude 25°30' to 27°30' South in Atacama Province, Chile.

2. METHOD OF STUDY

ERTS interpretations were mapped at 1:1,000,000 and later reduced to 1:2,650,000 for convenience, requiring one sheet (7 in. x 19 in.) for each subject. Page limitations prohibit their inclusion in this paper. The following have been identified on maps at 1:2,650,000: 1) 150 salars (areas of ground-water evapotranspiration); 2) 184 closed drainage basins; 3) geologic data: 681 volcanoes, faults, structural trends, diagrammatic fold axes, ancient Lake Minchin; 4) snow cover, August-October, 1972; 5) surface water, August-October, 1972: 88 seasonal lakes and floodwaters; 6) extent of 61 seasonal lakes and floodwaters, August-October, 1972; and 7) seasonal flooding versus snow cover, August-October, 1972: 40 basins having more than 40 percent snow cover, 17 basins having 20 to 40 percent snow cover, and 26 lakes larger than 1 square mile.

The basis for classification as <u>verified</u>, <u>modified</u>, or <u>revealed</u> by ERTS was chiefly the Operational Navigational Charts (ONC sheets P-26, Q-26, and Q-27) at 1:1,000,000, believed to be the best maps readily available in Washington, D.C. Better maps of some features are in compilation from aerial photographs for parts of the study area. In northern Chile salar borders interpreted from ERTS were compared to maps compiled from aerial photographs by the Geological Survey but not yet published.

The maps as compiled to date show corrected relative positions of features, but absolute corrections with respect to latitude and longitude have not yet been practicable. Corrections to date have been made in relation to about 250 high peaks, mostly volcanoes reaching altitudes of 14,000 to 22,000 feet, that were mapped by triangulation and are the most accurate features on existing maps. Horizontal positional discrepancies of 5 to 10 miles are common for drainage features on available published maps.

C8

3. STUDY OF SALARS OR SALT FLATS

Salars are largely evapotranspiration troughs where most of the ground water and surface water of closed basins is discharged. Accurate delineation of salars helps in estimating the area of a desert basin from which ground water is discharged by evaporation and transpiration, and helps assess water resources in areas where water is the major limitation on development. Prior to this study, there were positional discrepancies of as much as 10 to 15 miles in the portrayal of salars and other drainage features, particularly in Bolivia and Argentina.

Salars, mapped with the aid of ERTS imagery, number 150 and cover about 10,000 square miles in the study area. Of these, 86 proved essentially correct on published and unpublished maps, but borders were refined even on well-mapped salars. Thirty-two salars were significantly modified, and 20 were mapped solely from ERTS imagery.

4. STUDY OF CLOSED DRAINAGE BASINS[2/]

Delineation of drainage divides that define the perimeter of closed basins in arid to semiarid regions is basic to water-resources appraisal and is necessary for estimating runoff or flood probability. Also, distribution of saline minerals is related to both present and former drainage divides. Saline resources include sodium chloride, sodium sulfate, calcium sulfate, potash salts, nitrates, iodates, borates, and carbonates. In several basins the overflow of divides during an ancient pluvial age has flushed salts into lower basins.

Drainage basins between latitudes 21° and 25° South are outlined on Figure 2, based on available topographic maps with ERTS-assisted revisions. Steep relief in the Andes, where most of the basins occur, helps reveal divides by erosion features and snow-capped ridges. An average profile of an Andean drainage basin would be an area of 200 square miles, a basin floor altitude of about 13,500 feet, mean basin altitude more than 14,000 feet, mean relief more than 2,000 feet, mean altitude of perimeter divides more than 15,000 feet, and average slopes of terrain more than 6 percent. These unusual characteristics will be studied further with the aid of ERTS imagery in an attempt to relate them to runoff and flooding in future seasons.

2/ Closed basins, as used here, are basins having internal surface drainage; some are hydrologically open due to subsurface leakage.

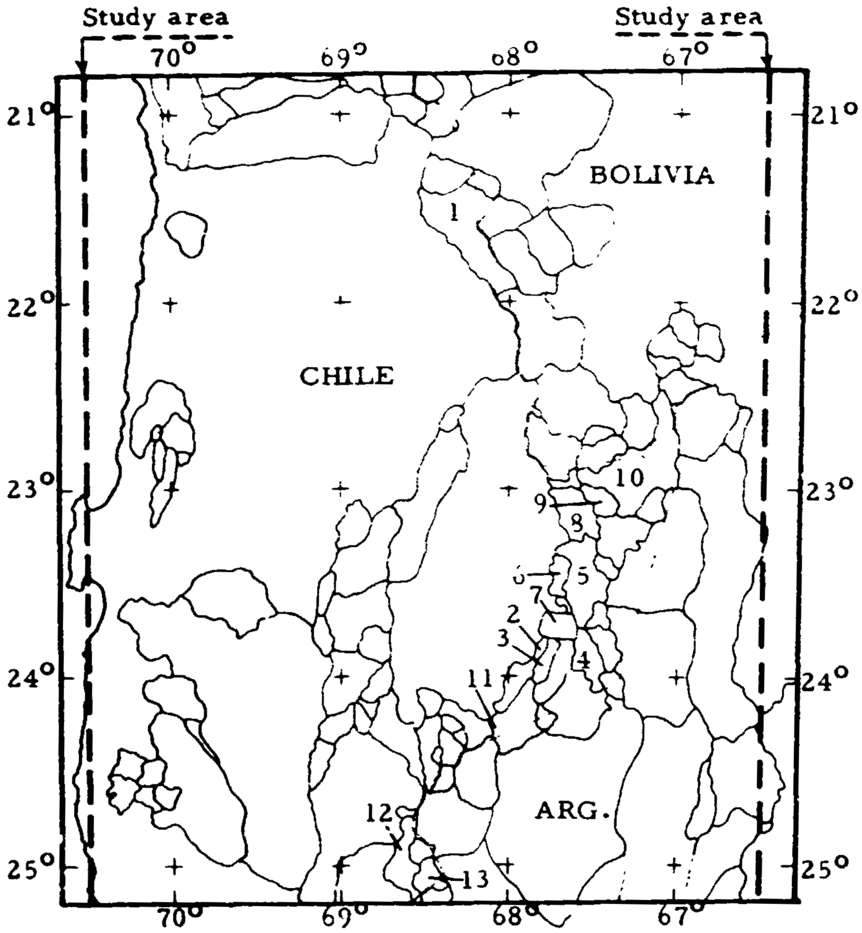

FIGURE 2. CLOSED DRAINAGE BASIN DIVIDES IN THE CENTRAL ANDES, 21° TO 25° S. Numbers refer to the 16 drainage basins summarized on Table 2; national borders shown by dotted line to distinguish from divides that coincide.

A total of 184 closed basins were mapped in the study area. ERTS images assisted in delineation of divides, particularly in the eastern half of the area, where reliable topographic maps were unavailable. However, the outlines of 47 basins are still unreliable, and future ERTS studies will be directed toward improving the reliability of these.

5. GEOLOGIC STUDIES

ERTS studies to date include delineation of volcanic craters, faults, structural trends, folds, and ancient lakebeds. Preliminary mapping covers large parts of the study area and will continue with acquisition of new imagery.

A published geologic map covering 3,600 square miles around Salar de Atacama (50 to 100 miles southeast of Chuquicamata, Chile) was experimentally evaluated using ERTS imagery. This established that refinements can be made in geologic maps with the aid of ERTS imagery, a task that could most effectively be done by geologists familiar with the areas.

Volcanic craters

Of 681 volcanoes, craters, and calderas mapped, 251 were verified, five were modified, and 171 were mapped from ERTS imagery; 230 more are shown on the Mapa Geologico de Chile (Instituto de Investigaciones Geologicas, 1968) but were unverified because of snow and cloud cover. Among nine active volcanoes, one was relocated 1.5 miles eastward; this is Volcan Parinacota (lat. 18°10' S). Fifteen calderas were mapped, 10 from previous sources and five from ERTS imagery.

Faults

Among the 5,000 linear miles of known faults in Chile between latitudes 17°30' and 25° South, about 1,500 miles could be traced on the imagery. An additional 160 linear miles of conjectural faults or realinements of known faults were mapped. The ERTS data would be most useful to geologists by delineating faults and permitting the extension of known faults as inferred or conjectural faults.

Fold axes

Major structural trends, principally fold axes, were mapped in Bolivia and Argentina, including an area of geologic interest where the Andean fold system bends around from a strike of N 40°W near La Paz, Bolivia, to N 15°E in northwestern Argentina. Detailed interpretation of geologic structures using ERTS images in an area of complex geology would require detailed knowledge of the geology. For example, in an area located 40 miles east-southeast of Uyuni a geologic map (Servicio Geologico de Bolivia, 1966, sheet 6332) shows that one straight northeastward traverse of 6-1/4 miles would cross 16 anticlinal axes and 16 synclinal axes, with an average spacing of one every 1,000 feet, a spacing equivalent to 32 fold axes per centimeter on ERTS imagery at 1:1,000,000.

6. STUDY OF SNOW COVER

The distribution of snow cover and surface water was studied to better understand present climate as it influences basin flooding and salt-crust morphology. This could help in understanding earlier climatic regimen, and possibly the distribution of saline resources such as the Chilean nitrate deposits. Currently the only climatic data available for most individual basins and ranges are extent of lakes or seasonal floodwaters and the distribution of snow cover. ERTS images have now made it possible to analyze both of these important parameters. These data are extremely important in understanding the water resources of mountainous areas where much of the water available to bordering lowlands originates. In the Andes, ERTS data are particularly valuable because meteorological and stream-gaging stations are scarce.

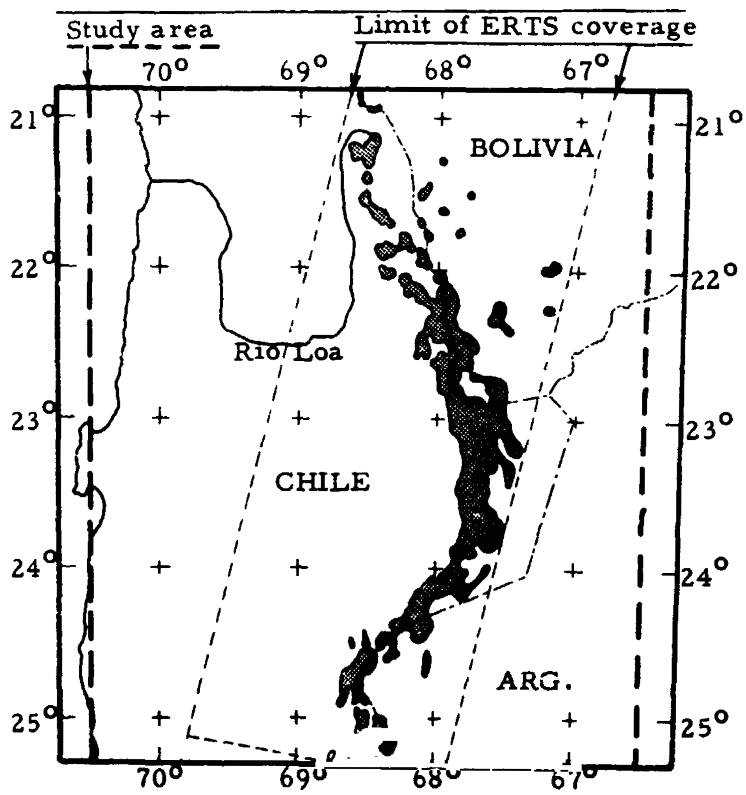

FIG. 3. ANDEAN SNOW COVER, 21° TO 25° S., OCT. 30, 1972.

Figure 3 shows the distribution of snow cover from latitude 21° to 25° South on the main Andean range on October 30, 1972. Earlier, on July 31, 1972, snow was seen to cover most of the range south of latitude 26° South, along the border between Chile and Argentina. The snow at that time covered most areas higher than 15,000 feet in the main range, while ridges extending higher than 20,000 feet 100 miles to the east were largely free of snow.

By October 30, 1972 (Fig. 3) the snow had the appearance of a heavy snowpack remaining after some melting. Snow cover was largely on the main range, extending to altitudes of about 15,000 feet on the east and to altitudes of 13,000 to 14,000 feet on the west. Additional snow cover probably lay along the border between Bolivia and Argentina but was outside the limits of ERTS coverage on October 30, 1972.

7. STUDY OF SURFACE WATER

Lakes or seasonal floodwaters were mapped at 88 places, of which 29 were lakes similar to those on existing maps, 23 were modified by ERTS data, and 36 were mapped solely from ERTS. The areas of 87 surface-water bodies are summarized in Table 1, totalling 493

Table 1. Distribution of 87 lakes and floodwaters in closed basins and deserts of South America, August-October, 1972 (excludes L. Titicaca)

Lake area, square miles	Northern one-third			Southern two-thirds			Whole study area		
	Lat. 16°30' - 20° S Long. 66°30'-70°30'W			Lat. 20° - 28° S Long. 66°30'-70°30'W			Lat. 16°30'-28° S Long. 66°30'-70°30' W		
	No.	Total area	Mean area	No.	Total area	Mean area	No.	Total area	Mean area
More than 16	4	308	77	0	0	0	4	308	77
8.1 - 16	1	11	11	3	37.5	12.5	4	48.5	12.1
4.1 - 8	2	12.2	6.1	6	32.9	5.5	8	45.1	5.6
2.1 - 4	2	6.7	3.4	10	31.0	3.1	12	37.7	3.1
1.1 - 2	3	4.4	1.5	19	29.3	1.5	22	33.7	1.5
0.5 - 1	6	4.7	0.8	16	11.1	0.7	22	15.8	0.7
0.1 - 0.4	7	1.5	0.2	8	2.4	0.3	15	3.9	0.3
Totals	25	349	- -	62	144	- -	87	493	5.7

square miles. Nearly all of this surface water is saline and unfit for use, because most is on the saline floors of closed basins. However, the use of ERTS imagery to monitor seasonal changes in floodwaters on basin floors provides an opportunity to evaluate areal and seasonal changes in weather, climate, and water resources in this relatively undeveloped region that lacks both data and water.

A special study was made of the relation between seasonal flooding and snow cover in the Andes between latitudes 21° and 25°20' South during August-October, 1972. Thirty-six basins larger than 60 square miles, with the best topographic and snowpack data were studied to find which general factors favor seasonal flooding.

Three factors correlated with the extent of surface water, and in lieu of better data might help to explain and predict future surface-water conditions (for example, lakes, flooding, and runoff) in many of the 184 closed basins as well as in the more poorly known external drainage basins. The gross factors are high basin altitudes, high perimeter divides, and high percentage of snow cover. Figure 4 illustrates that the best correlation between surface water, snow cover, and altitude in August-October is given by these values: 1) mean altitude of drainage basin 13,500 feet or higher; 2) mean altitude of drainage divides 14,500 feet or higher; and 3) snowpack covering more than 10 percent of the basin on October 30. Sixteen of the 36 basins met all three criteria, and 13 of these had surface water covering more than 1 square mile or more than 0.3 percent of the drainage basin. These were the only basins having ERTS snowcover data that had water areas as large as 1 square mile or as extensive as 0.3 percent of the drainage basin.

It is concluded that these 13 basins contain the most abundant surface water resources in the region. It should be useful to extend this ERTS application and similar studies to additional areas and during other seasons, as well as to attempt analysis of ground-water resources with the aid of ERTS imagery. Further data on 16 basins containing abundant water resources are given in Table 2.

8. REFERENCES CITED

Instituto de Investigaciones Geologicas, 1968: Mapa Geologico de Chile, 1:1,000,000

Servicio Geologico de Bolivia, 1966: Mapa Geologico de Bolivia, 1:100,000

Table 2. Sixteen basins larger than 60 square miles in northern Chile, containing lakes or floodwaters larger than 1 square mile or covering more than 0.3 percent of the drainage basin, August-October, 1972.

Key no., Fig. 2	Basin area (sq mi)	Mean basin altitude (feet) 1/	Mean altitude of divides (feet)	Snow cover (percent of basin, Oct. 30)	Water area (sq. mi., Aug.-Oct.)	Water (percent of basin)
1	640	14,000	15,500	13	1.4	0.22
2	75	13,500	14,500	64	3.2	4.3
3	156	13,500	14,500	33	3.2	2.1
4	175	14,750	16,000	21	1.1	0.63
5	400	14,750	16,000	38	1.4	0.35
6	91	14,750	15,800	99	0.7	0.77
7	124	15,000	16,600	97	4.1	3.3
8	252	15,500	16,000	84	2.3	0.91
9	104	13,750	15,200	43	2.5	2.4
10	711	14,250	16,000	15 2/	10	1.4
11	283	13,750	15,900	41	1.1	0.39
12	210	13,750	15,100	40	1.2	0.57
13	94	15,000	15,900	67	2.6	2.8
14	125	15,250	17,800	3/	2.2	1.8
15	684	16,000	17,400	3/	6.5	0.95
16	360	14,500	15,500	3/	12	3.5

1/ Mean altitude of basin is defined here as $\left(\frac{A+B}{2}\right)$ where A is altitude of lowest point, and B is mean altitude of perimeter divides.

2/ Snow covered 15 percent of area imaged by ERTS on October 30.

3/ Snow cover not available for October 30, but July 31 imagery suggests high percentage of snow cover.

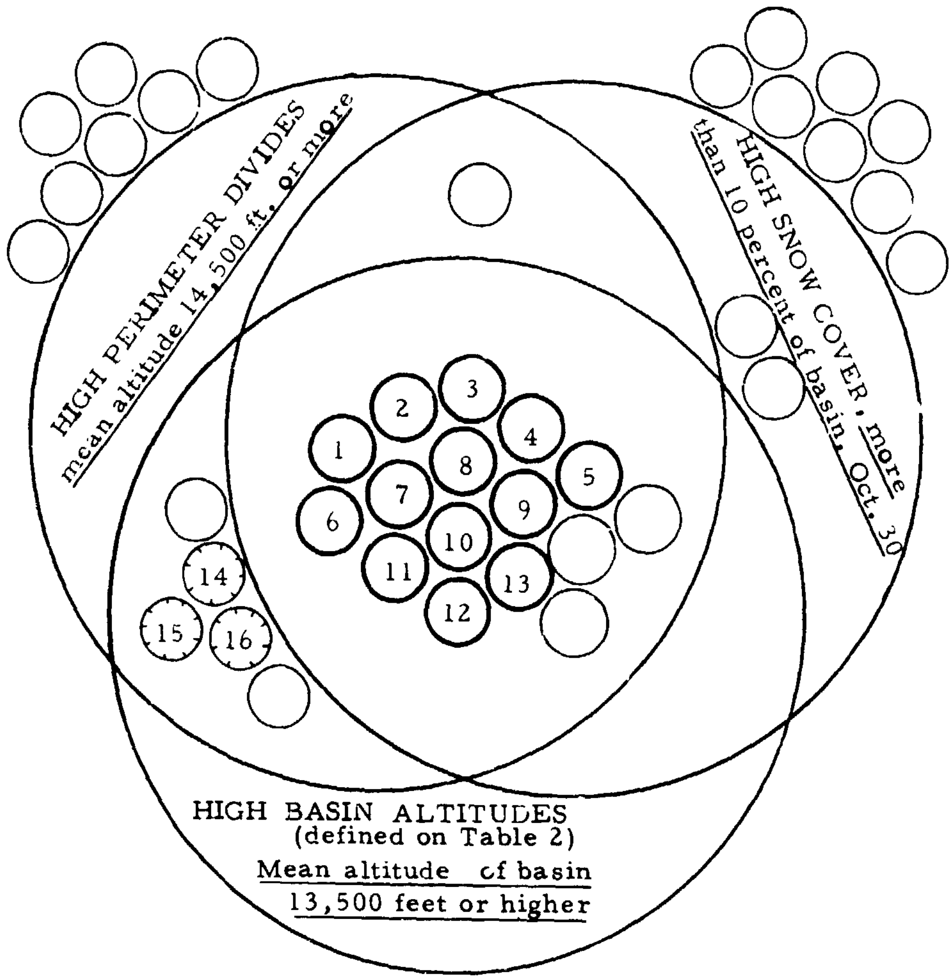

FIGURE 4. FACTORS FAVORING SEASONAL FLOODING IN 39 BASINS LARGER THAN 60 SQUARE MILES IN NORTHERN CHILE. Based on 36 basins for which snow-cover data from ERTS (Oct. 30, 1972) covers at least 30 percent of basin; includes 3 other basins known to contain perennial lakes larger than 2 square miles.

23 basins witnout lakes or floodwaters, or where water covered less than 1 sq. mi. and less than 0.3 % of basin, Aug.-Oct. 1972

3 — 13 basins where lakes or floodwaters covered more than 1 sq. mi. or 0.3 % of basin area; basins are identified on Figure 2.

14 — 3 basins known to contain perennial lakes over 2 square miles, but snow cover data were unavailable for October 1972; basins are summarized on Table 2.